Development Status of the Transport Gasifier at the PSDF

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ABSTRACT

The Power Systems Development Facility (PSDF) is an engineering scale demonstration of advanced coal-fired power systems and high-temperature, high-pressure gas filtration systems. The PSDF was designed at sufficient scale so that advanced power systems and components can be tested in an integrated fashion to provide data for commercial scale-up. The PSDF is funded by the U. S. Department of Energy, the Electric Power Research Institute, Southern Company, Foster Wheeler, Kellogg Brown & Root, Inc., Siemens-Westinghouse, Combustion Power Company and Peabody Holding Company.

A primary focus of the PSDF is to demonstrate and evaluate the Transport reactor and high-temperature, high-pressure particulate collection devices (PCDs), important components required for successful development of advanced power generation systems. The Transport reactor is an advanced circulating fluidized bed reactor designed to operate as either a pressurized combustor or a gasifier. The reactor operates at considerably higher circulation rates, velocities and riser densities than a conventional circulating bed, resulting in higher throughput, better mixing, and higher mass and heat transfer rates.

The Transport reactor was operated in combustion mode for approximately 5000 hours from 1996 - 1999 at a typical operating condition of 1625°F and 200 psig. The Transport reactor was reconfigured for gasification operations and began operation as a gasifier in September 1999. Over 1500 hours of gasification have been achieved to date with three different fuels.

Gasification was carried out at temperatures of 1600 to 1825°F and pressures of up to 240 psig, with coal flow rates of 2,500 to 6,000 pounds per hour. Gasifier performance was initially limited by an inability to maintain sufficient carbon in the circulating bed due to lower than expected char retention in the reactor loop. Modifications made to the solids collection system during 2000 improved the solids capture efficiency and operational stability of the system, allowing higher coal feed rates. The most fundamental change was the addition of the loop seal underneath the primary cyclone. Synthesis gas heating values of 80-120 Btu/SCF, coal carbon conversions over 90%, and hot gas efficiencies over 85% have been achieved. The highest heating values were obtained at the maximum coal feed rates.

An economic study of a commercial Transport Reactor Integrated Gasification system has been completed. It projected that a 298 MW (net) system based on a single GE 7FA gas turbine will cost $1,390/kW (all included) and have a heat rate of 8292 Btu/kW-hr (HHV).

INTRODUCTION

The Power Systems Development Facility (PSDF) is an engineering scale demonstration of advanced coal-fired power systems and high-temperature, high-pressure gas filtration systems (PSDF web site: "http://psdf.southernco.com/"). The PSDF was designed at sufficient scale so that advanced power systems and components can be tested in an integrated fashion to provide data for commercial scale-up. The PSDF is configured in two separate trains: the Transport reactor of Kellogg Brown & Root, Inc. (KBR) and the Foster Wheeler Advanced Pressurized Fluidized Bed Combustion system. Both trains contain a Siemens-Westinghouse Particulate Control Device (PCD) which use candle barrier filters to remove particulates.

A primary focus of the PSDF is to demonstrate and evaluate the Transport reactor and high-temperature, high-pressure particulate collection devices, important components required for successful development of advanced power generation systems. The synthesis gas from the Transport reactor in gasification mode could be used to fuel a combustion gas turbine or a fuel cell, or it could be processed into chemicals such as methanol or ammonia. The reactor operates at considerably higher circulation rates, velocities and riser densities than a conventional circulating bed, resulting in higher throughput, better mixing, and higher mass and heat transfer rates.

PROCESS DESCRIPTION

The Transport reactor, configured as a gasifier, consists of a mixing zone, riser, disengager, cyclone, standpipe, loop seal, and J-leg. A schematic of the Transport gasifier is shown in Figure 1. The fuel, sorbent, and air are mixed together in the mixing zone, along with recirculated solids from the standpipe. The gas with entrained solids moves up from the mixing zone into the riser, which has a slightly smaller diameter, makes two turns and enters the disengager. The disengager removes larger particles by gravity separation and then most of the remaining particles are removed in the cyclone. The solids collected by the disengager and cyclone are recycled to the mixing zone through the standpipe and J-leg.

Figure 2 is a process flow diagram of the Transport gasification system that includes the feed, waste solids, and gas systems. The fuel and sorbent are separately fed into the Transport gasifier through lock hoppers. The gas leaves the Transport reactor cyclone and goes through the primary gas cooler to the Siemens-Westinghouse PCD barrier filter, where ceramic or sintered metal candles filter out the dust . The PCD removes almost all the dust from the gas stream (to less than 1 part per million) to prevent erosion of a downstream gas turbine in a commercial plant. The operating temperature of the filter is determined by the gasifier temperature and the fraction of gas flow that bypasses the primary gas cooler. At typical gasifier temperatures, the PCD gas temperature can be controlled from 700 to 1,600°F by varying the bypass flow from zero to 100 percent. The filter candles are back-pulsed by high-pressure nitrogen at a fixed time interval or at a specified maximum pressure difference across the candles. A secondary gas cooler after the filter vessel cools the gas before it is discharged through a pressure let-down valve to the syngas combustor. The synthesis gas is sampled for on-line analysis both before and after the secondary gas cooler. In the syngas combustor all of the reduced sulfur compounds (H_2S, COS, CS_2) and reduced nitrogen compounds (NH_3, HCN) are oxidized.

The Transport gasifier produces a fine char/ash mixture that is collected by the PCD and a coarse char/ash mixture that is extracted from the Transport reactor standpipe. The two solid streams are cooled using screw coolers, depressurized in lock hoppers and then combined. The fuel sulfur captured by sorbent is present as calcium sulfide (CaS). The gasification char/ash mixture is combusted in an atmospheric fluidized bed combustor (AFBC) to oxidize the calcium sulfide to calcium sulfate ($CaSO_4$) and burn the residual carbon in the ash. The solids from the AFBC are then suitable for commercial use or disposal. Flue gas from the AFBC is combined with flue gas from the syngas combustor, sent to a baghouse, and then sent to the stack. The AFBC recovers the char/ash carbon heat content as superheated steam.

ACCOMPLISHMENTS AND RESULTS

The Transport reactor operated in combustion mode for approximately 5000 hours from 1997 through 1999 at a typical operating condition of 1625°F and 200 psig. Combustion heat was removed by a circulating solids cooler (not shown on Figures 1 & 2). Fuels used included three bituminous coals from Alabama, East Kentucky and Illinois, a mixture of three sub-bituminous coals from the Powder River Basin (PRB) in Wyoming, and petroleum coke from an Alabama refinery. Stable operations were demonstrated for all fuels and sorbents tested.

The Transport reactor was reconfigured in 1999 as a gasifier by removing the solids cooler from service and commissioning the AFBC and syngas combustor. The Transport reactor has operated for over 1500 hours in gasification mode, as of September, 2001. Fuels tested to date include a mixture of four different Powder River Basin Coals, an Illinois #6 coal from the Pattiki mine and an Alabama Calumet Mine bituminous coal. Figure 3 gives the operating history of the Transport reactor in combustion and gasification.

The first part of gasification characterization test GCT1 was successfully completed in September 1999 using the sub-bituminous Powder River Basin coals. After a two-month outage to evaluate gasifier and PCD performance, the second part of GCT1 started in December 1999 using the blend of Powder River Basin Coals and dolomite. During the run, the fuel was switched to Illinois #6 coal. The last day of operation was on Alabama bituminous coal. The gasification system was operated for 170 hours before being shut down. Five different feed combinations of coal and sorbent were tested to gain a better understanding of the solids collection efficiency. Figure 4 shows the gasifier temperature and pressure for the December part of the test run.

These first gasification tests were plagued by poor PCD cleaning due to high solids loading and uneven gasification system operations. Because of commissioning tests there were few periods of steady state operation, resulting in poor mass balances. The highest heating value achieved during December 1999 was with the PRB coal, since PRB is more reactive than Illinois #6 and Alabama bituminous coals. The test runs with bituminous coals were preliminary and of limited value; the carbon content in the circulating solids was extremely low due to inefficient recirculating solids collection.

The AFBC and syngas combustor were successfully operated during this first gasification test run. The AFBC oxidized calcium sulfides very well and consumed all of the carbon in the char/ash. The resulting solids passed the reactive sulfide test that is used to determine if the solids can be safely disposed. The sulfide levels in the AFBC solids during all PRB tests were below the detectable limit, while the sulfide oxidation for the Illinois #6 coal tests was up to 80%. The AFBC temperature was well controlled and there were no temperature excursions during the test. The syngas combustor operated well on the synthesis gas.

In the second gasification characterization test, GCT2, in April 2000, the unit operated for 217 hours using a blend of several Powder River Basin coals and Longview limestone from Alabama. The GCT2 test plan focused on analyzing the effects of different operating conditions on gasifier performance and operability. The recirculating solids collection system continued to operate poorly, so in the outage following GCT2 the Transport reactor loop was modified. The most important change was the addition of a loop seal underneath the primary cyclone and increasing the disengager length.

The third Gasification characterization test, GCT3, was planned primarily to commission the loop seal. After a successful hot solids circulation test (GCT3A), the second part of GCT3 (GCT3B) was started in January 2001 and completed in February 2001 after 184 hours of continuous operation on coal feed. During GCT3B a blend of several Powder River Basin coals was used with Bucyrus limestone from Ohio. The loop seal performed well, allowing much higher solids circulation rates and higher coal feed rates (Figure 5). These resulted in lower relative solids loading to the PCD and higher char retention in the reactor loop, giving a higher CO/CO_2 ratio and higher carbon conversion (Figure 6). The improved operability and efficiency of the recirculating solids collection system also resulted in a smaller fine char particle size to the PCD (Figure 7).

Figure 8 show temperature profiles at low and high solids circulation operating conditions. The increases and decreases in temperature in the mixing zone are due to the entry locations of the air, steam, nitrogen, coal feed, and sorbent feed. Both profiles show a general increase in temperature with height into the upper mixing zone then a decrease in temperatures as the solids and gas mixture moves up through the riser. However, the temperature decrease in the riser is higher for the low solids circulation operating period resulting in a lower solids temperature returning into the bottom of the mixing zone through the J-leg.

The final Gasification characterization test (GCT4) was completed in March 2001 after 242 hours of operation. A blend of several Powder River Basin coals with Bucyrus limestone from Ohio was used. Gasifier and PCD operations were stable, however, the coal feed system continued to have operational problems with fine coal grinds. Based on experience from this run, several modifications were made to the system. To prevent tar formation during startup, a coke breeze feed system was designed that would raise the gasifier temperature to above 1600 °F before starting coal feed.

The first Gasification Test Campaign, TC06, was started in July 2001, and the system was successfully transitioned from the Startup burner to coke breeze feed. The system was shutdown on July 21 to tune the main air compressor. During the tuning a thermal excursion occurred in the PCD, resulting in an extended outage. Coal feed was restarted on August 19 for the continuation of the test run, which is still ongoing as of September, 2001. Gasifier and PCD operations have been extremely stable with a continuous operation of more than 500 hours, giving several extended steady state periods for performance analysis.

Figure 9 shows gasifier temperature and pressure data. Synthesis gas heating values over 100 Btu/SCF, and coal carbon conversions over 85%, have been achieved (Figure 10). Figure 11 shows the normalized baseline and peak differential pressures across the PCD for the test run to date. Figure 12 shows the transient PCD differential pressure with a backpulse interval of 10 minutes. The PCD differential pressure decreases from 175 to 125 in H_2O after backpulsing the top plenum and then decreases from 140 to 90 in H_2O after backpulsing the bottom plenum.

COMMERCIAL DESIGN STUDY

A conceptual plant design and cost estimate were completed for a commercial power system design using the transport gasifier. A simplified process flow diagram of the Transport Reactor Integrated Gasification (TRIG) process is given in Figure 13. Major design bases are as follows.

<u>Gasifier</u>

- air-blown transport gasifier at 400 psia and 1800°F, 95% carbon conversion
- dry feed of low sulfur Powder River Basin sub-bituminous coal to gasifier
- sorbent injection into gasifier to control SOx
- syngas filter operates at 750°F with sintered metal candles

<u>Combustor</u>

- air-blown transport char combustor at 350 psia and 1600°F, >99.9% carbon conversion
- vitiated air filter operates at 1000°F with sintered metal candles
- clean vitiated air produces power through a hot gas expander/generator

<u>Combined Cycle</u>

- one modified GE 7FA gas turbine flat-rated at 197 MW by varying extraction air flow
- process air supplied by a gas turbine extraction (boosted) and a supplementary air compressor
- steam is generated in HRSG and by cooling syngas, vitiated air, and combustor solids
- steam cycle conditions: 1820 psia / 1000°F / 1000°F
- combined cycle designed to operate on natural gas as a backup fuel
- Selective Catalytic Reduction system in the HRSG to reduce NOx emissions

Performance of this system was calculated to be 298.4 MW net power, with a heat rate of 8,292 Btu/kW-hr (HHV) during normal operation at average annual ambient conditions. When operating on the backup fuel, the system generates 280.9 MW at a heat rate of 7,943 Btu/kW-hr (HHV). More performance details are given in Table 1.

Emissions are low for a coal-based power plant, with SO_X calculated at 0.10 lb/MMBtu and NO_X at 0.07 lb/MMBtu. Estimated emissions of some regulated and unregulated species are given in three different units of measure in Table 2.

Capital costs of the TRIG system are based on a typical Greenfield southeastern United States location. The all-included capital requirement for the TRIG system is $414.7 million, which is $1390/kW. The costs are broken out by major functional areas in Figure 14. This cost was increased by the conservative approach taken in using only near-term commercially available equipment and a relatively small 1 x 1 combined cycle configuration.

ACKNOWLEDGEMENTS

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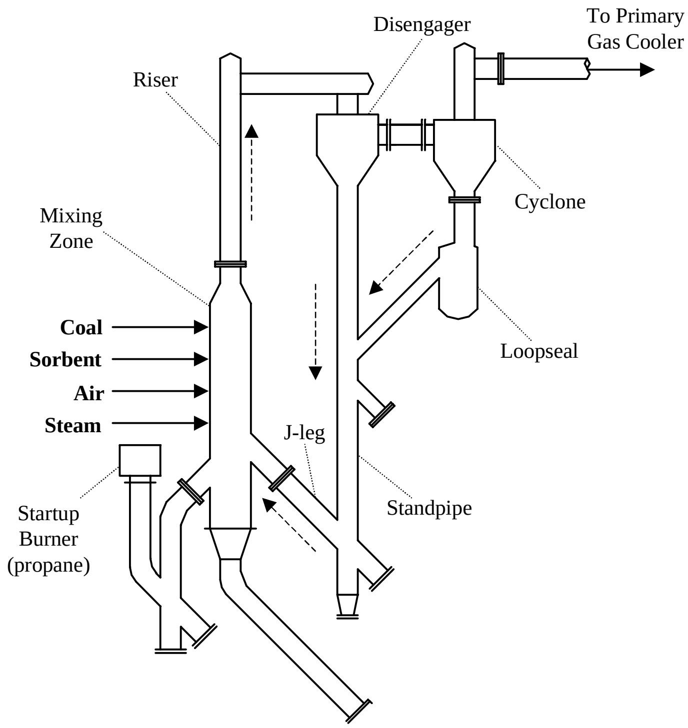

Figure 1 – Transport Gasifier

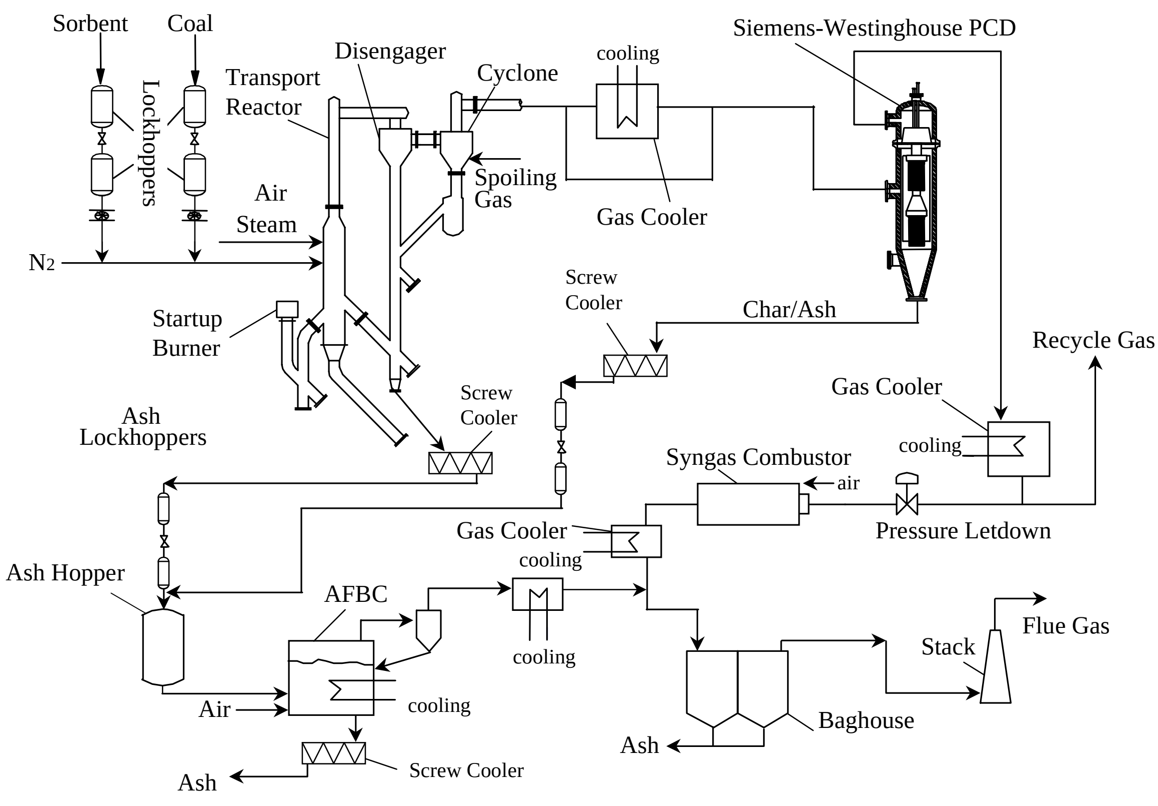

Figure 2 – Transport Gasification System

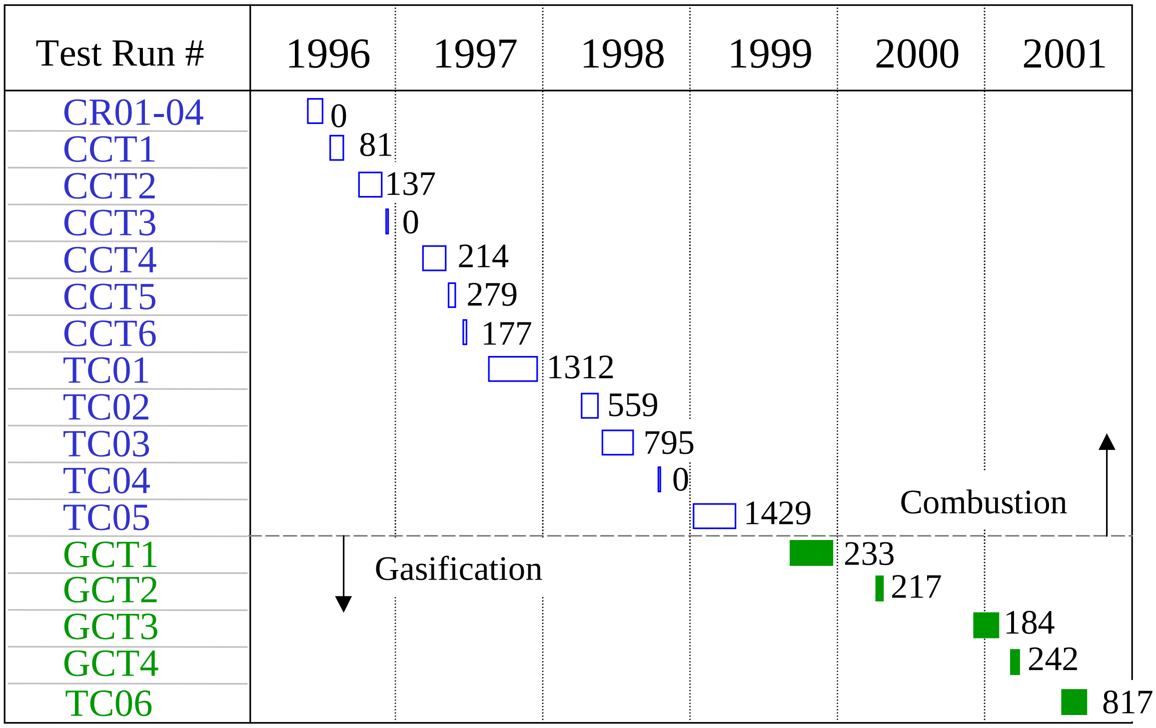

Figure 3 – Transport Reactor Test Run Summary (NOTE: TC06 was in progress as of September, 2001)

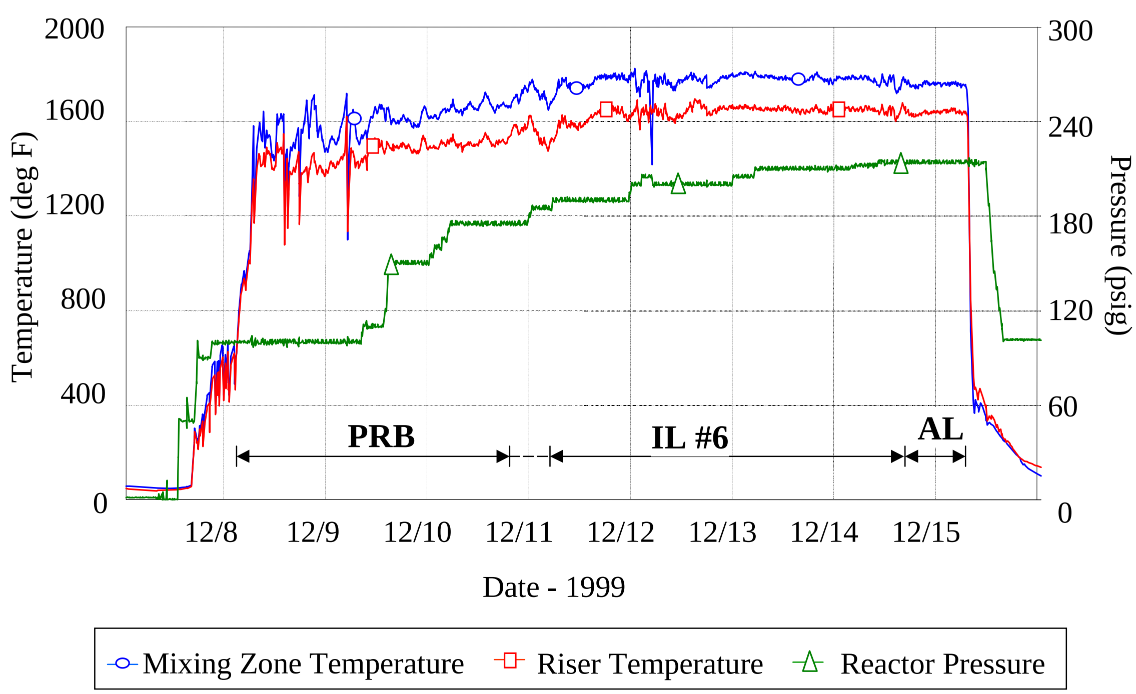

Figure 4 – GCT1 Temperature and Pressure Data

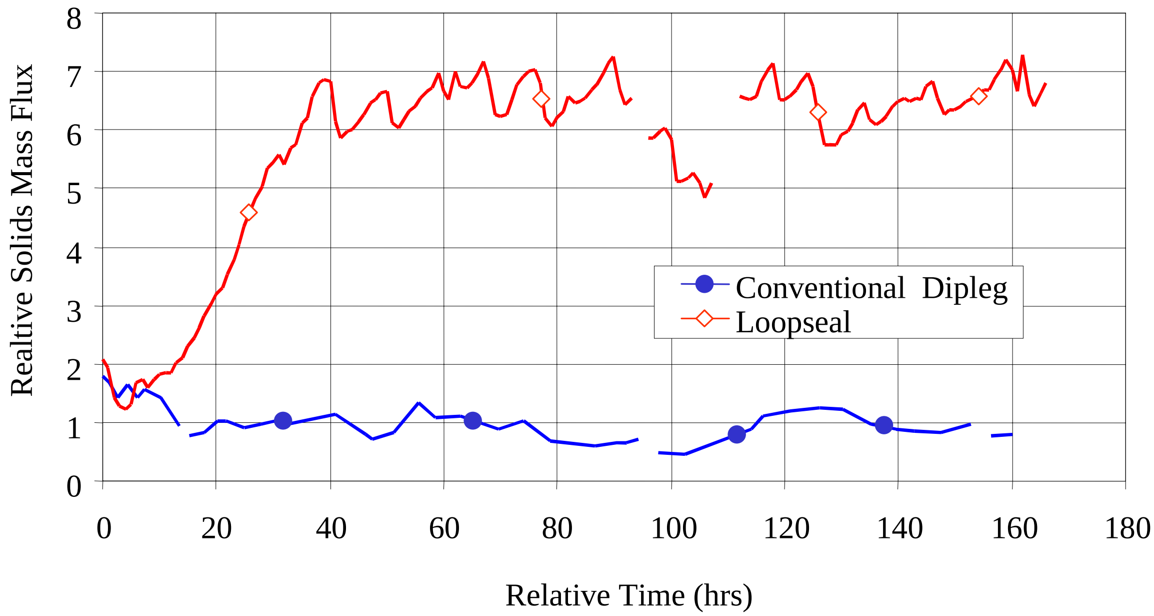

Figure 5 – Relative Solids Mass Flux Before and After Loop Seal Addition

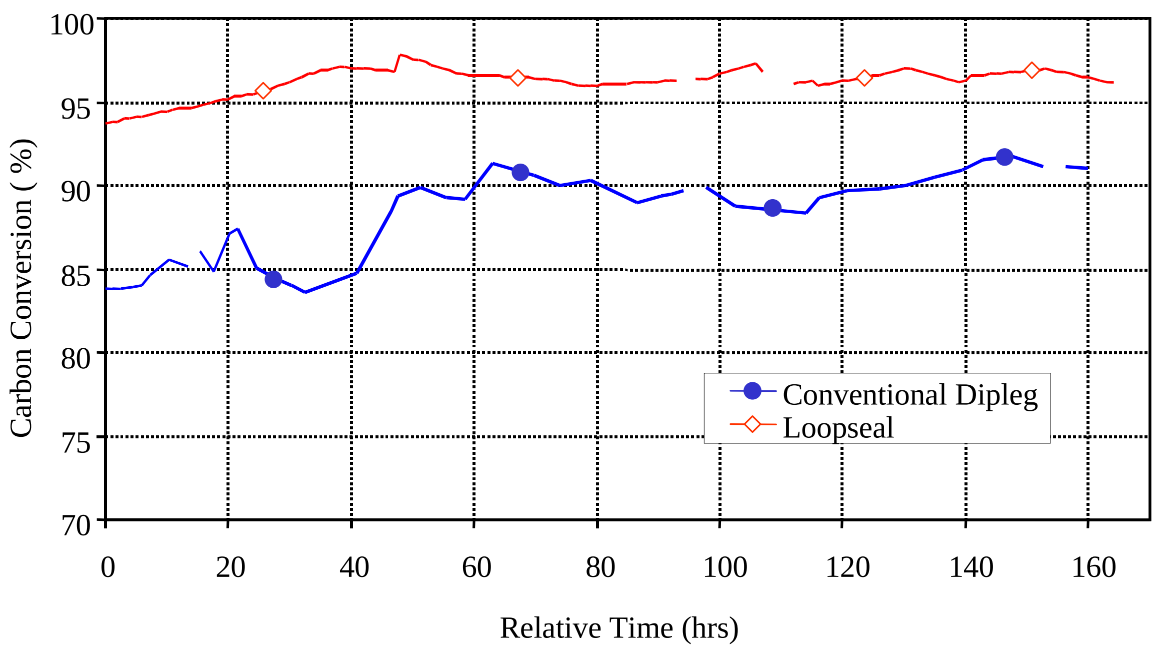

Figure 6 – Carbon Conversion Before and After Loop Seal Addition

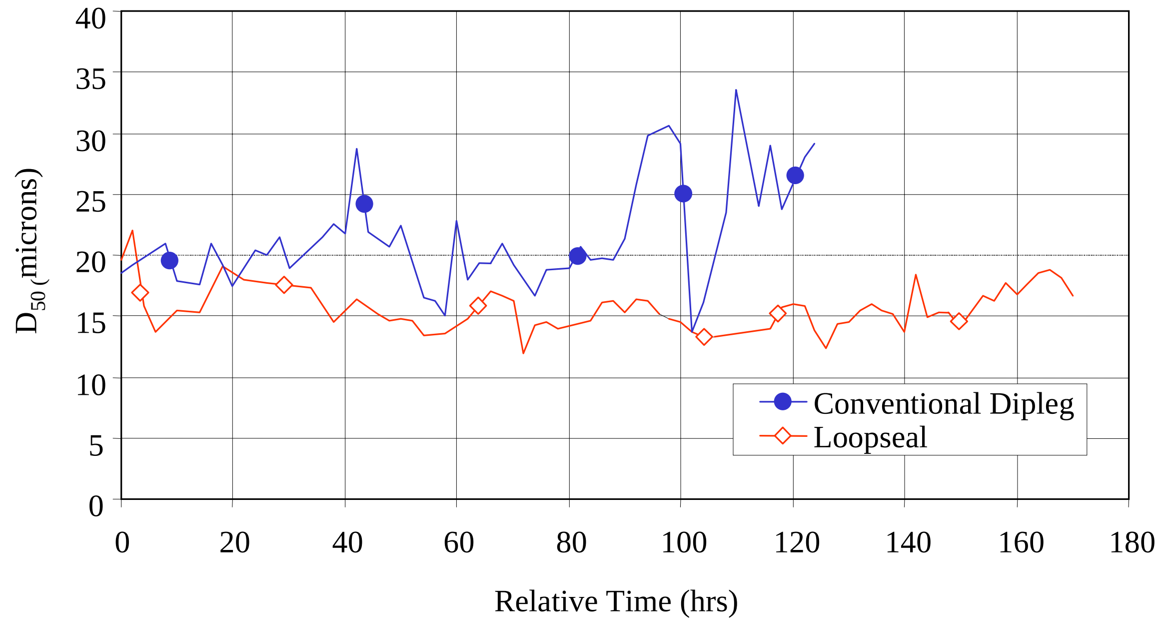

Figure 7 – Fine Char Particle Size Before and After Loop Seal Addition

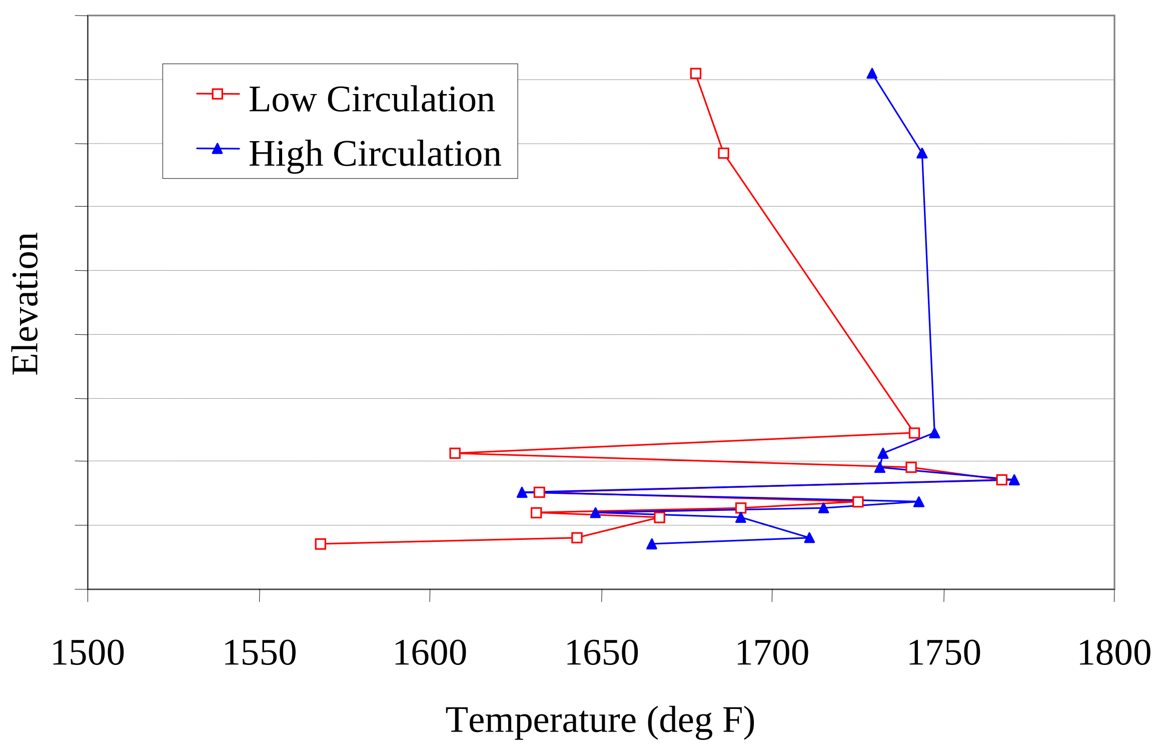

Figure 8 – Temperature profiles for low solids circulation rates during GCT2 and GCT4

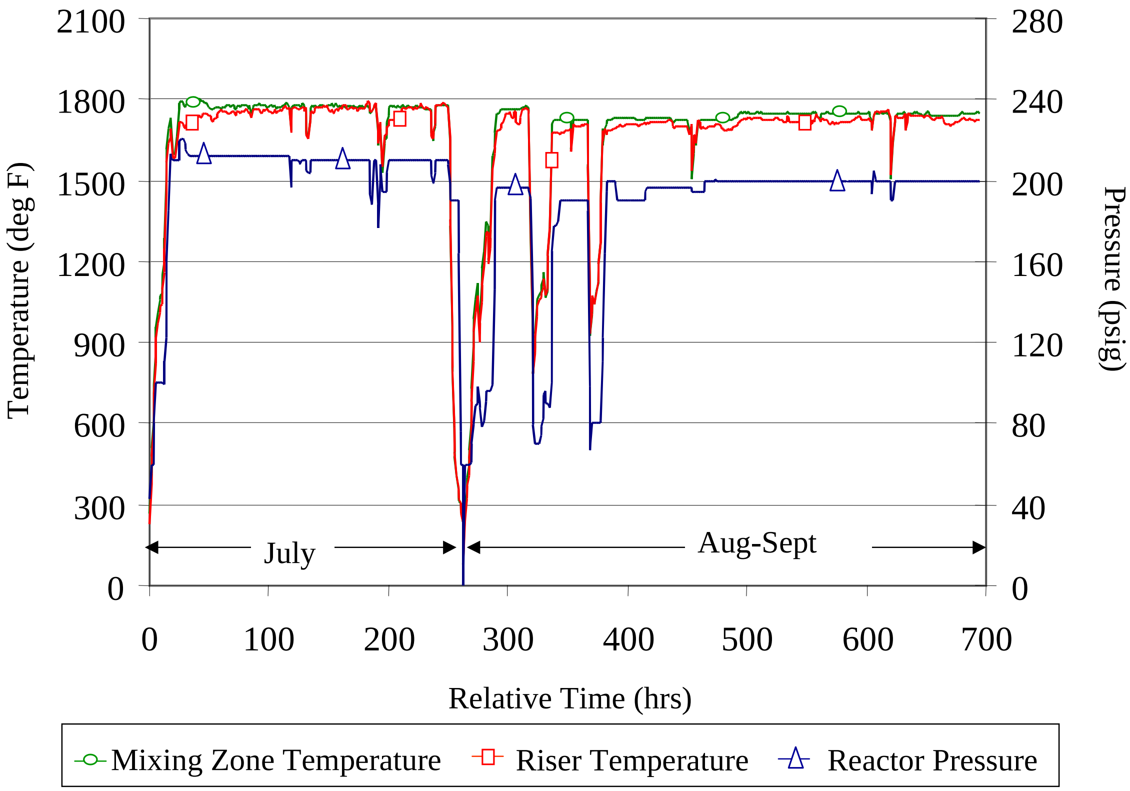

Figure 9 – TC06 Temperature and Pressure Data

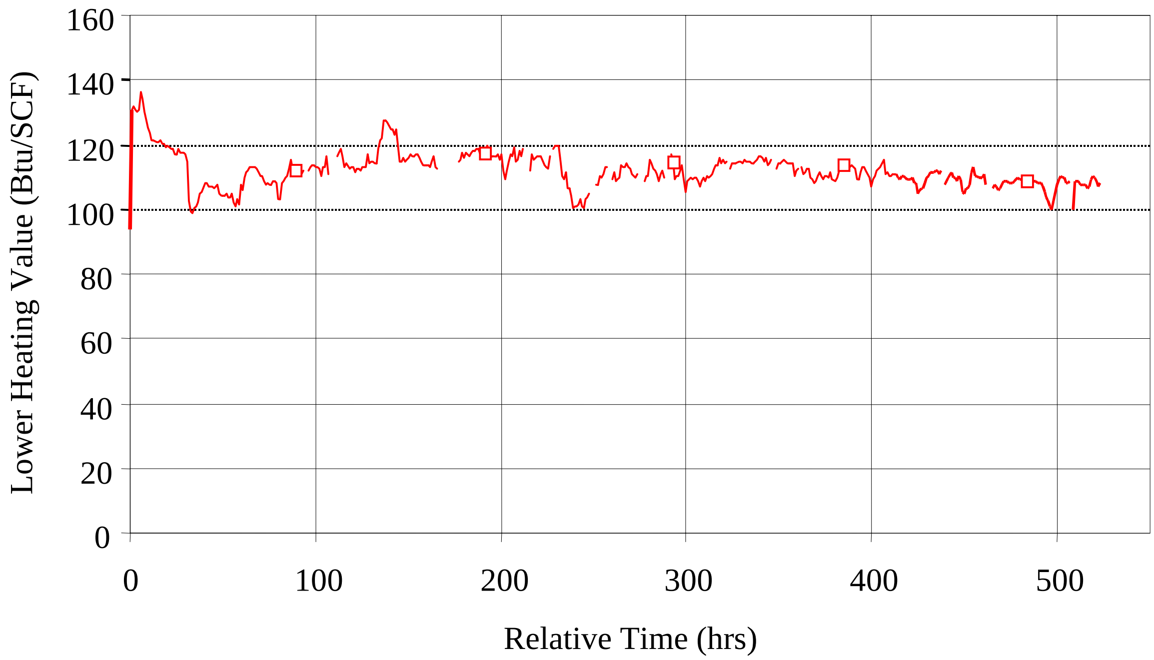

Figure 10 – TC06 Syngas Heating Value

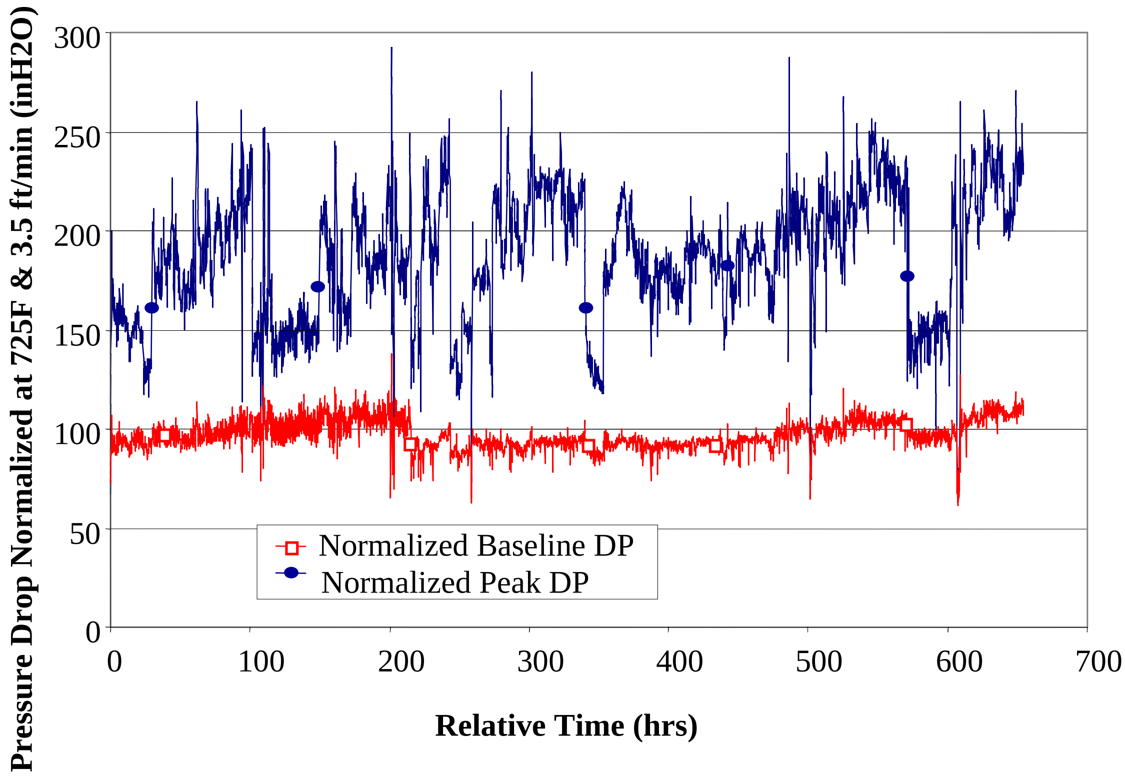

Figure 11 – TC06 PCD Normalized Baseline and Peak Differential Pressure

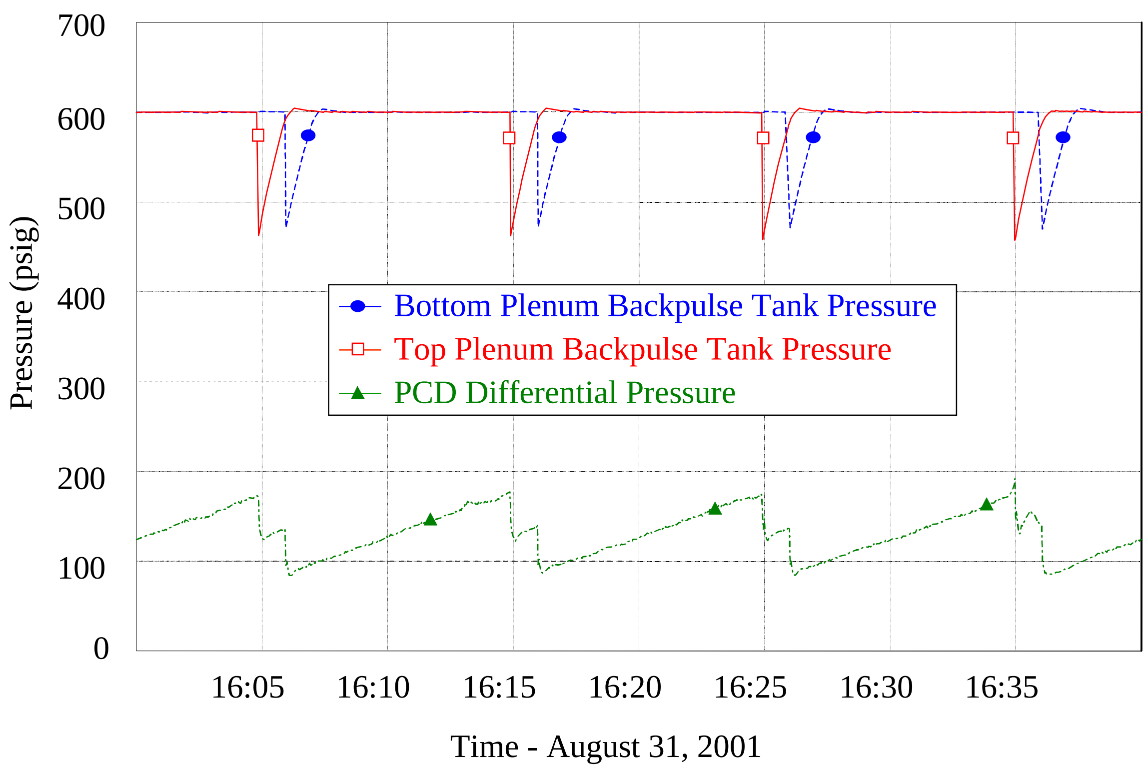

Figure 12 – PCD Top and Bottom Plenum Backpulse Tank Pressure and PCD Differential Pressure on August 31, 2001

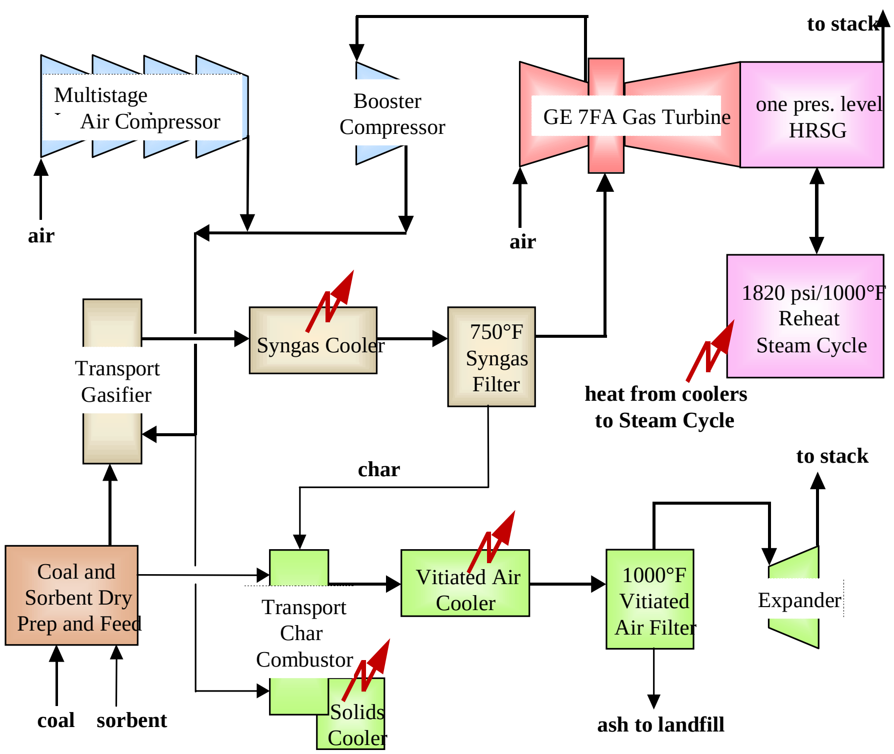

Figure 13. Simplified TRIG Process Flow Diagram

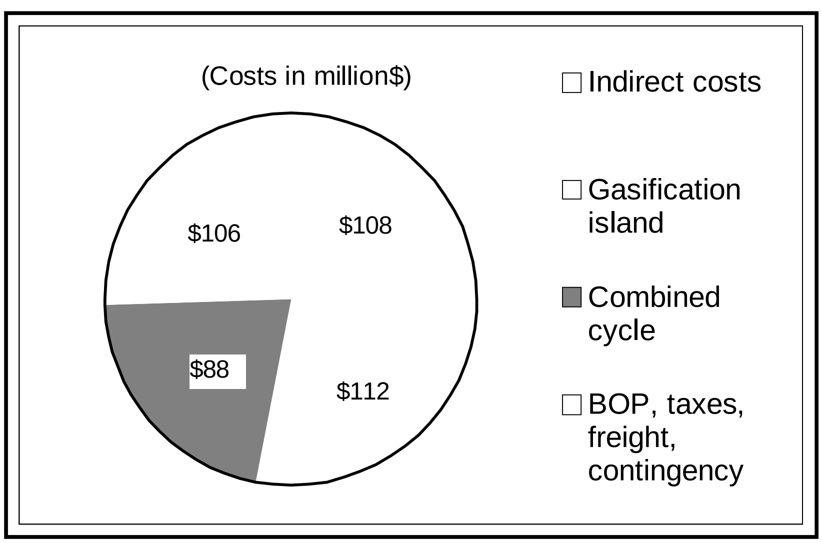

Figure 14. TRIG Capital Costs Broken Out by Major Functional Area

Table 1. TRIG Plant Performance at 65°F and 60% Relative Humidity

	on syngas	on natural gas	
Gas Turbine Gross Output	197,000	162,000	kW
Steam Turbine Gross Output	120,806	127,645	kW
Char Combustor Gas Expander Gross Output	5,193	0	kW
Auxiliary Load	24,647	8,742	kW
Net Power Output	298,351	280,903	kW
Heat Input From Coal (HHV)	2,435	0	MMBtu/hr
Heat Input From Natural Gas (HHV)	39	2,231	MMBtu/hr
Net Heat Rate (HHV), High Side of GSU	8,292	7,943	Btu/kW-hr
Net Efficiency (HHV)	41.2	42.96	%
Heat Input From Coal (LHV)	2,300	0	MMBtu/hr
Heat Input From Natural Gas (LHV)	35	2,011	MMBtu/hr
Net Heat Rate (LHV), High Side of GSU	7,827	7,158	Btu/kW-hr
Net Efficiency (LHV)	43.6	47.67	%

Table 2. Estimated Emissions for TRIG Plant

	lb/MMBtu	ppmv	lb/MW-hr
NOx	0.07	27	0.59
SOx	0.10	27	0.78
CO_2	217	--	1770
CO	0.05	30	0.39
VOC	0.01	3.0	0.06
particulates	0.002	1.0*	0.014

* particulates concentration is reported in ppmw